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Quantitative land evaluation implemented in Dutch water management

M.J.D. Hack-ten Broeke[a,*], H.M. Mulder[a], R.P. Bartholomeus[b,c], J.C. van Dam[c], G. Holshof[d], I.E. Hoving[d], D.J.J. Walvoort[a], M. Heinen[a], J.G. Kroes[a], P.J.T. van Bakel[e], I. Supit[a], A.J.W. de Wit[a], R. Ruijtenberg[f]

[a] Wageningen Environmental Research, Wageningen Research, PO Box 47, 6700 AA Wageningen, the Netherlands
[b] KWR Watercycle Research Institute, PO Box 1072, 3430 BB Nieuwegein, the Netherlands
[c] Wageningen University, Soil Physics and Land Management Group, PO Box 47, 6700 AA Wageningen, the Netherlands
[d] Wageningen Livestock Research, Wageningen Research, PO Box 338, 6700 AH Wageningen, the Netherlands
[e] De Bakelse Stroom, Simon Vestdijkstraat 15, 6708 NW Wageningen, the Netherlands
[f] STOWA, postbus 2180, 3800 CD Amersfoort, the Netherlands

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ABSTRACT

Both in land evaluation and in water management quantitative methods, GIS and simulation modelling are well-known techniques for quantifying the effects of changes, such as land use or climate change. For hydrological management decisions information is often required on the effect of those decisions on agricultural production. To serve the needs of different types of users, like water authorities, provinces, drinking water companies and the National Department of Infrastructure and Water Management we developed a toolbox named WaterVision Agriculture as an instrument that can determine effects on crop yield and the farm economy as a result of drought, too wet or too saline conditions for both current and future climatic conditions.

WaterVision Agriculture is based on the hydrological simulation model SWAP, the crop growth model WOFOST and farm management and economic assessments such as DairyWise for dairy farming. The WaterVision Agriculture (WVA) project resulted in two products, namely i) an easily applicable tool (also called the WVA-table) and ii) the operational models for hydrology and crop growth SWAP and WOFOST for calculating effects on field scale combined with calculating farm economic results and indirect effects. SWAP simulates water transport in the unsaturated zone using meteorological data, boundary conditions (like groundwater level or drainage) and soil parameters. WOFOST simulates crop growth as a function of meteorological conditions and crop parameters. Using the combination of these process-based models and methods for describing crop management and economic value we derived a meta-model, i.e. a set of easily applicable simplified relations for assessing crop growth as a function of soil type and groundwater level. These relations are based on multiple model runs for at least 72 soil units and the possible groundwater regimes in the Netherlands. The easily applicable tool (WVA-table) uses this meta-model.

Applying the meta-model of WaterVision Agriculture should allow for better decisions on land use or soil and water management because the instrument can help to quantify the effects of changes in climate, land use, hydrological conditions or combinations of these effects on agricultural production.

1. Introduction

Land evaluation can be described as a process for defining the suitability of land for a certain land use. Land evaluation methods have been mostly adopted by soil scientists for predicting potentials of land in the view of changes, such as a new crop rotation, new management practices, changes in water management and in more recent years also climate change. FAO (1976) distinguished two types of land evaluation, namely physical and economic evaluation. Most studies however have focused on physical land evaluation alone. Simulation modelling and Geographical Information Systems (GIS) have greatly enhanced the possibilities for this physical evaluation, often in terms of quantifying crop productivity or specific land qualities (e.g. Bouma and Van Lanen, 1987; Bouma and Bregt, 1989; Hack-ten Broeke et al., 1989; Van Diepen et al., 1991; Van Lanen et al., 1992a; Bouma, 2000; Bonfante and Bouma, 2015; Bouma and Wösten, 2016).

* Corresponding author.
E-mail address: mirjam.hack@wur.nl (M.J.D. Hack-ten Broeke).

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Not only methods based on simulation models and GIS are common land evaluation methods. More qualitative assessments, based on experiments or expert knowledge can also be very useful (Sonneveld et al., 2010). There are various ways to distinguish different land evaluation methods and it is also possible to combine methods, depending on the required results, the relevant scale and on data availability. Van Lanen et al. (1992b,c) successfully combined qualitative and quantitative land evaluation for assessments at the scale of the Netherlands and the European Union.

Land evaluation methods are not restricted to soil science related studies. Sonneveld et al. (2010) noticed that "…The application domain of land evaluation procedures has nowadays been broadened from land use and land allocation to optimum sustainable resource use, and from land use planning to environmental impact assessments and risk assessments, from one-time assessments to continuous monitoring of environmental changes, and to analysis of past trends and future projections, as in scenario studies. It is in this whole new field of interdisciplinary applications that the kind of interpretation procedures as developed originally for land evaluation can make a contribution…".

In this paper we focus on a contribution of quantified physical and economic land evaluation for water management in relation to agricultural land use. The system we developed is called WaterVision Agriculture (in Dutch: Waterwijzer Landbouw). A large part of the method was described by Hack-ten Broeke et al. (2016).

Rossiter (1996) wrote "…A fundamental challenge facing land evaluation is to prove its relevance to the many pressing land-use problems of our day. Predictions of land performance, no matter how soundly based, are only useful if they will be used by decision makers, including individual land users, groups, or governments, to make better land-use decisions…" and "…Land evaluators should also accept that not only professional land-use planners have relevant questions, and that not only soil scientists and agronomists have relevant knowledge…" In a reaction Bouma (1996) adds the following: "…In addition, our clients have changed, simulation models and expert systems have been developed, and we have learned that yield alone is certainly not a measure for "suitability", but that the soil system should function harmoniously in wider agro-ecosystems to have a fair chance of being sustainable. And what about the term "suitability" in this context? In my experience, there is an increasing number of users who are not primarily interested in our judgment about suitabilities of a piece of land for a given Land Use System (LUS). Rather, they want us to give them different realistic options for land use for a given piece of land, with proper technical coefficients…".

In water management quantitative methods, GIS and simulation modelling are well-known techniques to produce different realistic options for current and future conditions. For hydrological management decisions information is often required on the effect of those decisions on agricultural production. Land evaluation methods can be very useful for this purpose. To serve the needs of different types of users, like water authorities, provinces, drinking water companies and the National Department of Infrastructure and Water Management we developed a tool named WaterVision Agriculture as an instrument that can determine crop yield effects and the effects on farm economy as a result of drought, too wet or too saline conditions for both current and future climatic conditions based on simulation modelling. In that sense WaterVision Agriculture can be considered as a quantitative physical land evaluation method combined with an economic assessment. The WaterVision Agriculture project resulted in two products, namely i) an easily applicable tool for quantifying effects of too dry, too wet or too saline conditions for current and future climate (also called the WVA-table) and ii) the operational models for hydrology and crop growth SWAP-WOFOST for calculating effects on field scale combined with calculating farm economic results and indirect effects.

In this paper the recent developments of WaterVision Agriculture are described as well as the models on which the instrument is based. We show examples of using this instrument for assessments of hydrological and climate change effects on agriculture for different crops, soil types and groundwater regimes. The examples will show how quantitative physical and economic land evaluation methods are helpful for decision making towards soil and water management for current and future climate.

2. Materials and methods

In WaterVision Agriculture the agrohydrological simulation model SWAP (Van Dam et al., 2008; Kroes et al., 2017) and the crop growth simulation model WOFOST (Van Diepen et al., 1989) together form the core of the process-based calculation of crop yields as a function of soil moisture conditions. We have linked these models on a daily basis to ensure realistic interaction between water in the root zone and crop growth. For instance: dynamic root growth as a function of weather and soil conditions instead of assuming a static rooting depth will influence water uptake and yield reduction, caused by drought or oxygen stress. This will reduce leaf area and this in turn will reduce transpiration in a more realistic way than assuming average annual crop development. Furthermore the linkage of these models (SWAP-WOFOST) enables us to assess the effects of future climate on the interaction between hydrology and crop growth, as it accounts for the interacting processes in the soil-water-plant-atmosphere system. For economic assessments for dairy farming we linked the system DairyWise (in Dutch: BBPR; Schils et al., 2007) to SWAP-WOFOST. DairyWise simulates grassland management and farm scale economics for dairy farms with different conditions in terms of for instance land and cattle. For arable crops and vegetables we use current prices for calculating economic effects of yield differences.

Based on these models we have arrived at an easily applicable land evaluation method with direct relationships between groundwater characteristics and crop yield. For this we have derived a meta-model, which mimics the relevant processes involved and generates roughly the same model results as the SWAP-WOFOST model would do, using much less input data (Hack-ten Broeke et al., 2016).

2.1. SWAP

The SWAP (Soil-Water-Atmosphere-Plant; Van Dam et al., 2008; Kroes et al., 2017) model is the hydrological core of WaterVision Agriculture. The model simulates water flow in relation to weather conditions in the unsaturated and saturated upper part of the soil profile, where the interaction between groundwater and surface water is important. The model SWAP calculates the water transport, dissolved substances and soil temperature (Fig. 1).

Water transport simulation is based on the Richards equation with a variable sink term for root water extraction. The potential transpiration rate depends on atmospheric conditions (air temperature, wind speed, solar radiation and air humidity) and plant characteristics (reflection coefficient, stomatal resistance, plant height and leaf area index). The potential root water extraction rate at a certain depth, $S_p(z)$ (d^{-1}), is considered to be proportional to the root length density and the potential transpiration rate:

$$S_p(z) = \frac{L_{root}(z)}{\int_{-D_{root}}^{0} L_{root}(z)dz} T_p$$

with L_{root} the root length density (cm^{-2}) and D_{root} the root layer thickness (cm).

Stresses due to dry or wet conditions and/or high salinity concentrations may reduce $S_p(z)$. The drought stress in SWAP is described by the dry part of the reduction function proposed by Feddes et al. (1978), which is depicted in Fig. 2a. In the moderate pressure head range $h > h_3$ root water uptake is optimal. Below h_3 root water uptake linearly declines due to drought until zero at h_4 (wilting point). The critical pressure head h_3 increases for higher potential transpiration

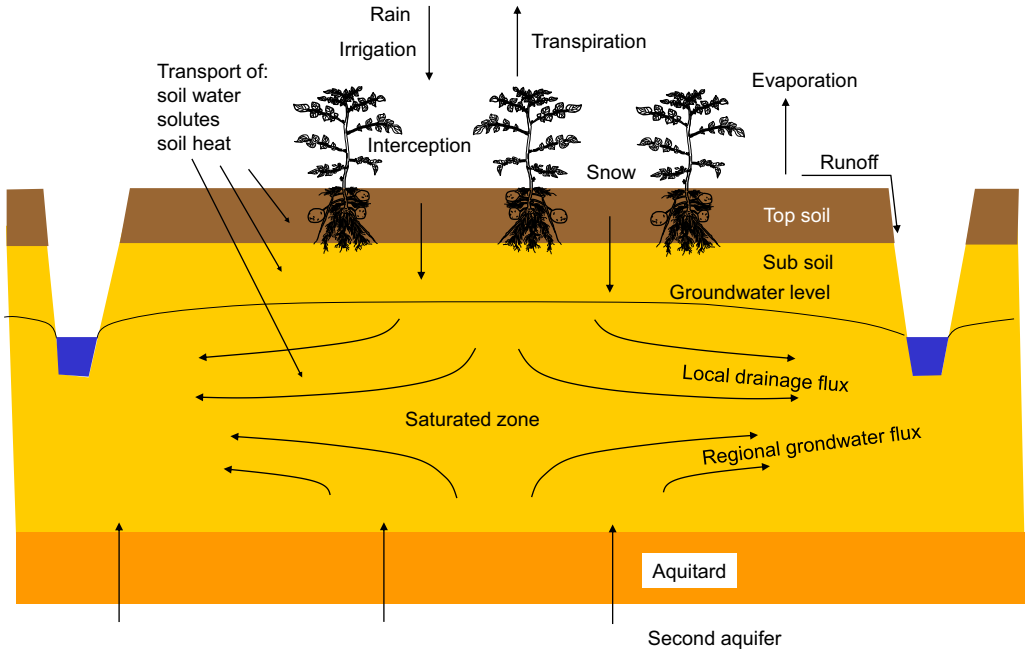

Fig. 1. Transport processes and modelling domain of SWAP; figure also used by Hack-ten Broeke et al. (2016).

rates of T_p.

Oxygen stress, defined as daily respiration reduction (i.e. potential minus actual respiration) is calculated with the process-based method of Bartholomeus et al. (2008) for oxygen transport and consumption, which uses generally applied physiological and physical relationships to calculate both the oxygen demand of and the oxygen supply to plant roots (Fig. 3). Oxygen stress occurs when the actual root respiration is lower than the potential root respiration, i.e. when the oxygen supply cannot meet the oxygen demand of plant roots. Root respiration is determined by interacting respiratory (i.e. oxygen consuming) and diffusive (i.e. oxygen providing) processes in and to the soil. The method of Bartholomeus et al. (2008) is applied to all soil layers of SWAP, to account for layer-specific soil physical properties, moisture contents and temperatures.

SWAP uses the response function of Maas and Hoffman (1977) for salinity stress (Fig. 2b). Below the critical concentration of EC_{max} (dS/m) no salinity stress is assumed. At salinity levels above EC_{max} the root water uptake declines with a constant slope of EC_{slope} (m/dS). The actual root water flux, $S_a(z)$ (d^{-1}) is derived in SWAP by multiplication of the stress factors due to drought, oxygen and salt stress:

$$S_a(z) = \alpha_d(z)\alpha_o(z)\alpha_s(z)S_p(z)$$

where α_d (−), α_o (−) and α_s (−) are reduction factors due to drought, oxygen and salinity stress, respectively.

Integration of the actual root water flux over the root zone yields the actual transpiration rate T_a (cm d^{-1}):

$$T_a = \int_{-D_{root}}^{0} S_a(z)\partial z$$

The SWAP user manual and website describe the theoretical background in detail as well as model input and applications (Kroes et al., 2017). SWAP is developed and maintained by Wageningen University and Research centre.

2.2. WOFOST

The underlying principles of WOFOST have been discussed by Van Keulen and Wolf (1986). The initial version was developed by the Centre for World Food Studies in Wageningen (Van Diepen et al., 1989). The basic processes simulated by WOFOST are phenological development, biomass growth, its partitioning over plant organs, root growth and the soil water balance. The most important external drivers are daily weather data. Other external drivers are initial soil and crop conditions. The most important internal driver is the leaf area index (LAI) which is the result of the leaf area dynamics controlled by

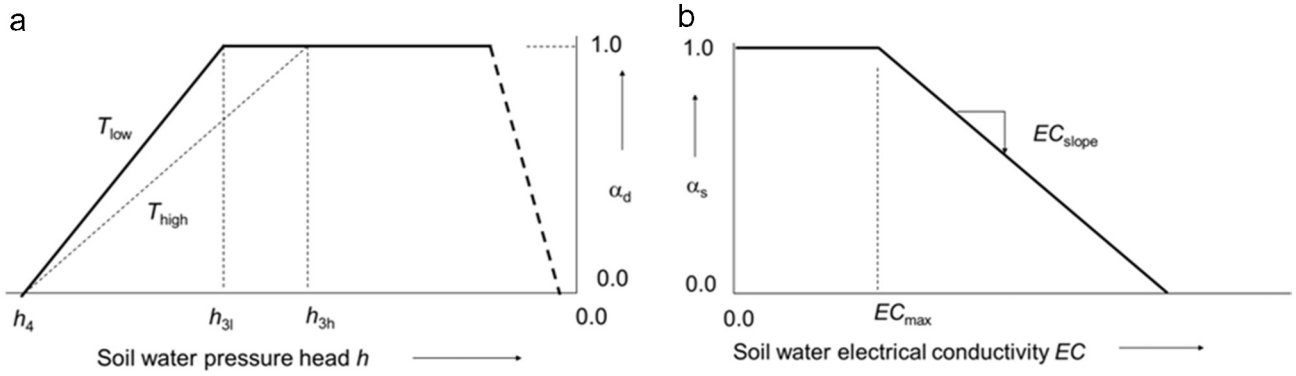

Fig. 2. a. Transpiration reduction factor α_s as function of soil water pressure head and b. transpiration reduction factor α_s as function of soil water electrical conductivity.

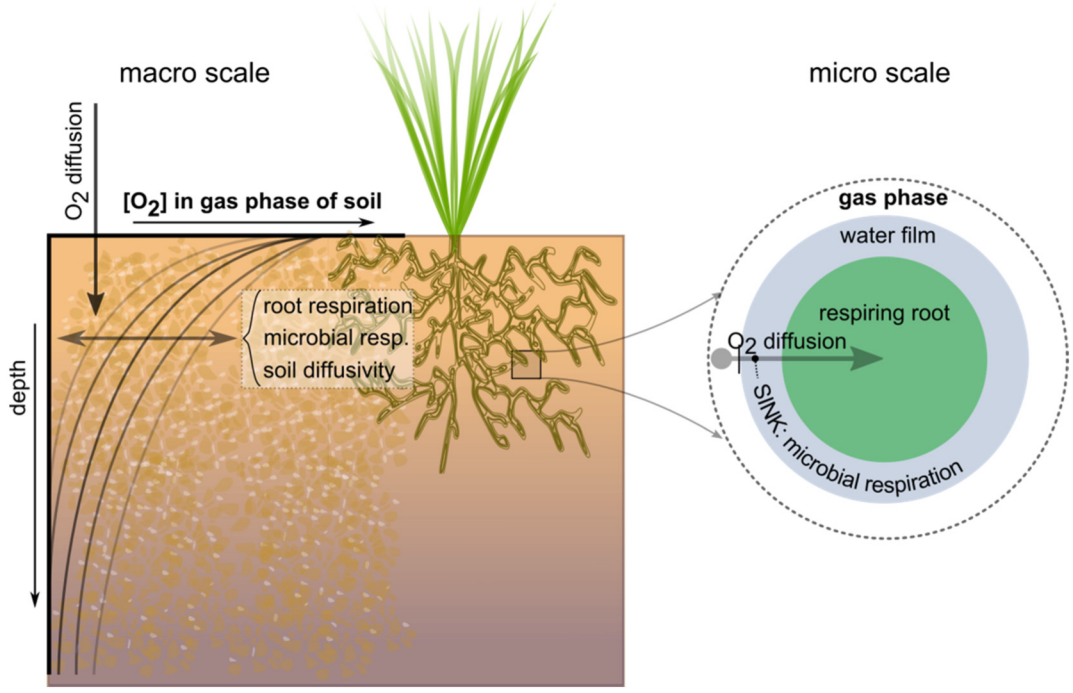

Fig. 3. Schematization of the oxygen module used to simulate daily respiration reduction. The model combines interacting physiological processes (i.e. root respiration and microbial respiration) and physical processes (i.e. macro-scale and micro-scale oxygen diffusion). Details of equations involved are given in Bartholomeus et al. (2008).
Figure taken from Bartholomeus et al. (2012).

photosynthesis, allocation of biomass to leaves, leaf age and development stage. In turn, LAI controls the daily rates of photosynthesis and evapotranspiration.

Currently, WOFOST as described by Kroes et al. (2017) and De Wit et al. (2018) is able to simulate potential production as governed by atmospheric conditions and plant characteristics, and limited production due to water, oxygen and/or salinity stress. Fig. 4 shows the processes and relations incorporated in WOFOST. The radiation energy absorbed by the canopy is a function of incoming radiation and crop leaf area. Using the absorbed radiation and taking into account photosynthetic leaf characteristics, the potential photosynthesis is calculated. The latter is reduced due to water, oxygen and/or salinity stress, as quantified by the relative transpiration (T_a/T_p), and yields the actual photosynthesis.

Part of the carbohydrates (CH_2O) produced are used to provide energy for the maintenance of the living biomass (maintenance

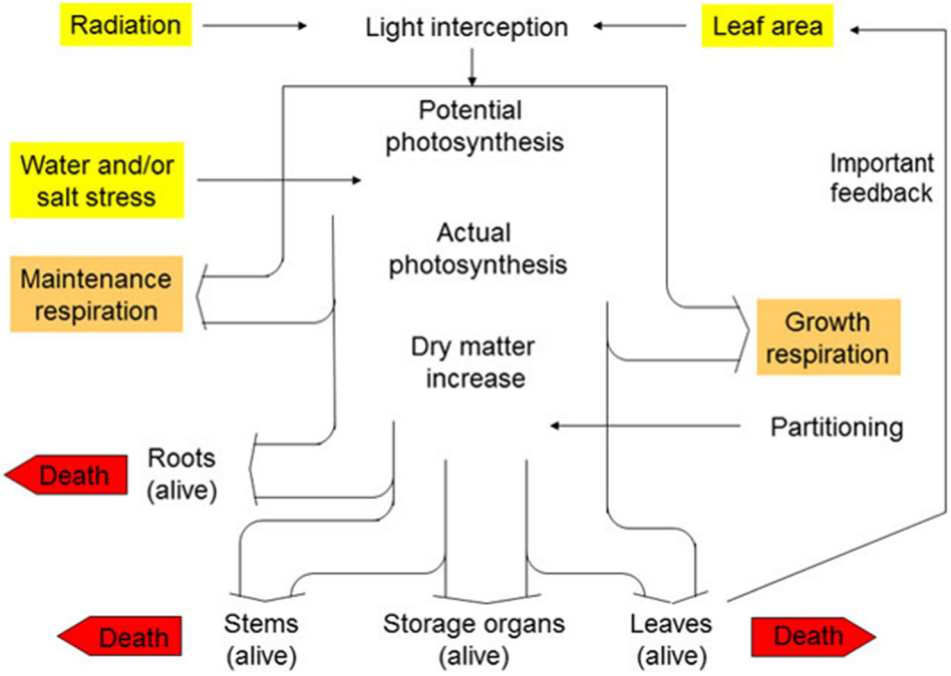

Fig. 4. Flow chart of crop growth processes included in WOFOST.

respiration). The remaining carbohydrates are converted into structural matter. In this conversion, some of the weight is lost as growth respiration. The dry matter produced is partitioned among roots, leaves, stems and storage organs, using partitioning factors that are a function of the crop development stage. The amount partitioned to the leaves determines leaf area development and hence the capacity of light interception. This interaction of light interception and leaf area growth is a very important positive feedback in WOFOST. The dry weights of the various plant organs are obtained by integrating their growth rates over time. During the development of the crop, part of the living biomass dies due to senescence.

2.3. DairyWise

The DairyWise model is an empirical model that simulates technical, environmental, and financial processes on a dairy farm (Schils et al., 2007). The central component is the FeedSupply model that balances the herd requirements, as generated by the DairyHerd model, and the supply of home grown feeds, as generated by the crop models for grassland and corn silage. When linked with the simulation models for soil-water-plant-atmosphere interactions within WaterVision Agriculture the crop modelling in DairyWise is replaced by SWAP-WOFOST. The output of the FeedSupply model is used as input for several technical, environmental, and economic sub-models. The sub-models simulate a range of farm aspects such as nitrogen and phosphorus cycling, energy use, and a financial farm budget. The final output then is a farm plan describing all material and nutrient flows and the consequences on the environment and economy. In the model combination within WaterVision Agriculture, DairyWise is a powerful tool for integrated scenario development, for adding especially grassland management to this land evaluation tool, allowing also the quantification of farm economic results (Knotters et al., 2017).

2.4. Meta-model

The combined models as described in Sections 2.1, 2.2 and 2.3 can be used on field and farm level for analysing specific situations using detailed soil information, crop data, weather data and hydrological data etc. The linked models of WaterVision Agriculture were tested and evaluated using experimental datasets (Hack-ten Broeke et al., 2016; Kroes et al., 2015; Knotters et al., 2017).

For regional assessments or land evaluation and water management studies on regional and national scale, we derived a tool based on a meta-model. The definition of a meta-model, also in WaterVision Agriculture (WVA), is a simple model derived from another more complex model. In the case of the linked SWAP-WOFOST model this means that the meta-model of SWAP-WOFOST must be able to simulate crop growth as if it was directly calculated using SWAP-WOFOST. A meta-model thus models the model results from another model (the original model). The linkage with DairyWise for the meta-model was conducted by adding the specific rules for simulating grassland management and economic assessments to SWAP-WOFOST.

The advantage of having a meta-model is that it requires much less input data than the original model. For SWAP-WOFOST simulations for instance we need a soil profile description with hydraulic characteristics and a large number of crop characteristics. For using the meta-model we only need to know soil type and crop type. This makes the meta-model much easier to use and it speeds up the calculations. Based on the input data like crop characteristics, soil properties and meteorological data and on the output data (crop yields and groundwater characteristics) of the complex process-based model SWAP-WOFOST, simple meta-models have been fitted that relate groundwater characteristics to crop yield and crop damage. These meta-models emulate the relevant processes involved and generate roughly the same model results as the SWAP-WOFOST model would do.

The meta-models we use for WaterVision Agriculture are so called random forests (Breiman, 2001). Random forests consist of many (usually several hundreds of) classifications or regression trees (CART-models). In our case, we have grown forests with regression trees. Each regression tree predicts crop growth given a set of explanatory variables like crop type, soil type, meteorological district, climate scenario, and several groundwater characteristics (e.g. mean groundwater level, mean highest groundwater level, mean lowest groundwater level). Starting at the trunk of a regression tree, the data are recursively split into smaller parts based on simple rules like “IF soil type is sandy loam THEN follow the left branch down the tree ELSE follow the right branch down the tree”. Each branch of the tree is split in turn until a terminal leaf is reached. This leaf contains a prediction (in our case crop growth). Instead of a single tree, random forests employ an entire ensemble of regression trees (forest of trees) to improve prediction accuracy by averaging the predictions of all individual regression trees. Each regression tree is constructed given a bootstrap sample of the original data. A bootstrap sample is obtained by sampling the original data with replacement. The size of each bootstrap sample is equal to the size of the original data. See Breiman (2001) for more details about random forests.

For deriving the meta-model, the SWAP-WOFOST combination was run for a period of thirty years for each combination of crop (15), soil unit of the Dutch soil physical database (72), weather station (5), climate conditions (2) and lower boundary conditions (100). Lower boundary conditions have been drawn by means of Latin hypercube sampling. This sampling method enforces an efficient coverage of the parameter space. Each run with the SWAP-WOFOST model results in many outputs. Of these outputs, we used 30-year average crop yield and crop damage as response variables, and groundwater characteristics like the mean highest groundwater level and the mean lowest groundwater level as explanatory variables of the meta-model.

Meteorological data were available from the Royal Netherlands Meteorological Institute KNMI. This data involves daily global radiation, minimum and maximum temperature, air humidity, wind speed, rainfall amounts and duration for five weather stations in the Netherlands for 30-year periods. KNMI provides current weather data for the period 1981–2010 as well as projected data for 30-year periods around 2050 for different climate scenarios (KNMI, 2014).

Soil profile information was obtained from the BOFEK 2012 database (Wösten et al., 2013). It contains soil physical data for 72 representative soil profiles covering the whole of the Netherlands.

The meta-model is also known as the WaterVision Agriculture table (WVA-table) and can be applied for quantifying agricultural yield for any given region in the Netherlands on the basis of soil type, groundwater characteristics, weather station and crop type. The WVA-table distinguishes the effects of drought and water excess on yield, directly related to reduced crop transpiration and also the so-called indirect effects.

Indirect effects on agricultural yield are the result of for instance a) suboptimal hydrological conditions or cold weather affecting workability or bearing capacity inducing a late start of the growing season or b) late crop emergence as a result of low soil temperature or c) hydrological conditions hindering harvest, mowing or grazing. Reduced crop yield can thus be attributed to direct drought stress or oxygen stress in the root zone or to indirect effects. The occurrence of these indirect effects is simulated along with the other effects with the SWAP-WOFOST model because soil moisture conditions and soil temperature in the root zone are both simulated with the model. For the different management types like sowing or planting and harvesting different crop dependent threshold values for the pressure head in the root zone are used. These define workability and bearing capacity, similar as performed by Bouma and Van Lanen (1987).

In the case of irrigation an extra input parameter is required, namely the salt concentration in irrigation water. This allows the quantification of crop yield reduction by the WVA-table due to salty conditions in the root zone for crops like potato and vegetables.

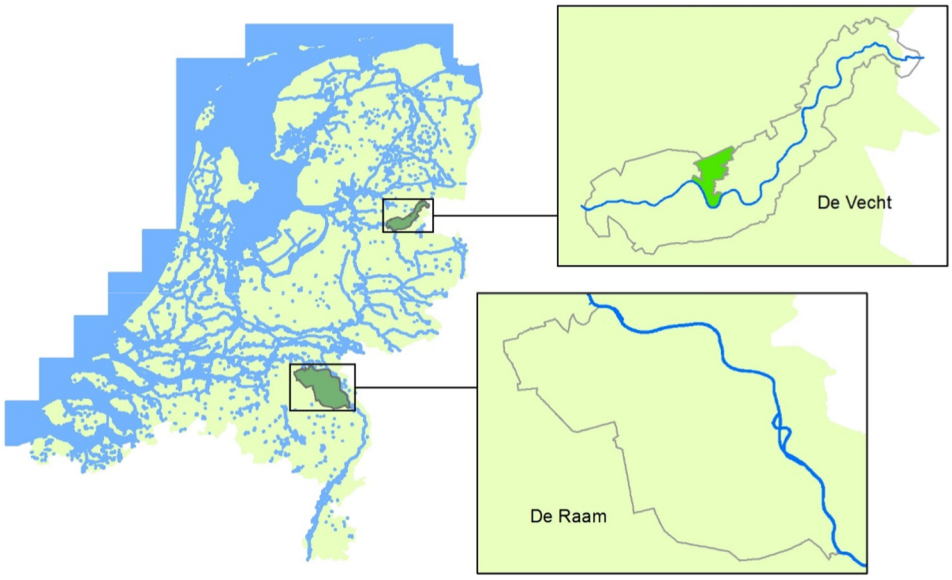

Fig. 5. Location of two pilot regions in the Netherlands: De Raam and De Vecht.

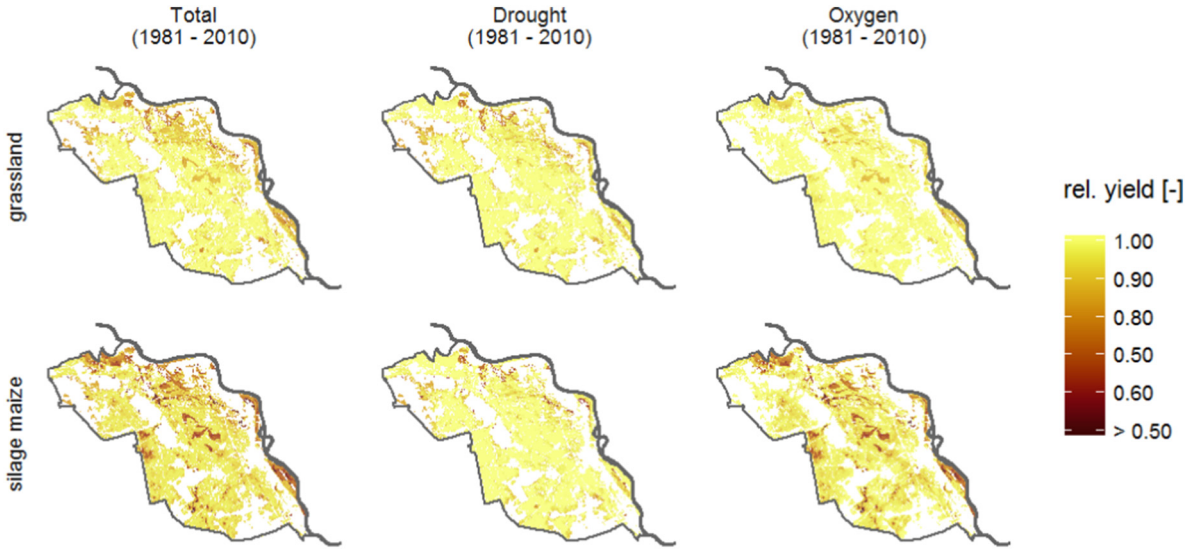

Fig. 6. 30-year average relative yield for grassland (above) and silage maize (below) for pilot area De Raam as quantified with WaterVision Agriculture (WVA-table). The relative yield is given as a percentage of the potential yield. The total relative yield is shown on the left, the part of this yield as affected by drought stress only is shown in the middle and the relative yield as effected by water excess only (i.e. oxygen stress) is shown on the right.

2.5. Pilot regions

The WVA-table was applied to two regions in the Netherlands (Fig. 5), namely in the south (De Raam) and east (De Vecht) of the country. In both regions most of the soils are sandy (Heinen et al., 2017). In the area De Raam 33 units of the soil physical database BOFEK occur, but 78% of the area consists of slightly loamy sandy soils (mostly Podzols and Cambisols (IUSS Working Group WRB, 2015)). In the area De Vecht this is similar with 22 units of the BOFEK-database and 83% of the area consisting of sandy soils.

The questions of the water authorities for the pilot application of the WVA-table were different. For De Vecht we focused on the effect of a potential wetting scheme as well as the potential effect of climate change for the area and for De Raam the water authority was mainly interested in the differences between hydrological years focusing on relatively dry and relatively wet growing seasons. For both regions only grassland and silage maize were evaluated.

3. Results

3.1. Examples for application of the meta-model (WVA-table) at regional scale

For the area De Raam the 30-year average relative yield is shown in Fig. 6 for both grassland and silage maize. The WVA-table is applied as if the land use of the total area is either only grassland or only silage maize. The grassland was considered to be only used for cutting and not grazing. Especially silage maize seems to encounter suboptimal hydrological conditions according to Fig. 6. When the effects of drought and oxygen stress are presented separately (also Fig. 6) it is obvious that for silage maize the area De Raam is mostly too wet. This is due to relatively shallow groundwater levels. In the case of grassland suboptimal conditions for agriculture are not very pronounced.

In many cases it is not only interesting to know the effect of soil and hydrological conditions in terms of 30-year averages, but also to know what may happen in individual years. In Fig. 7 this is illustrated for the

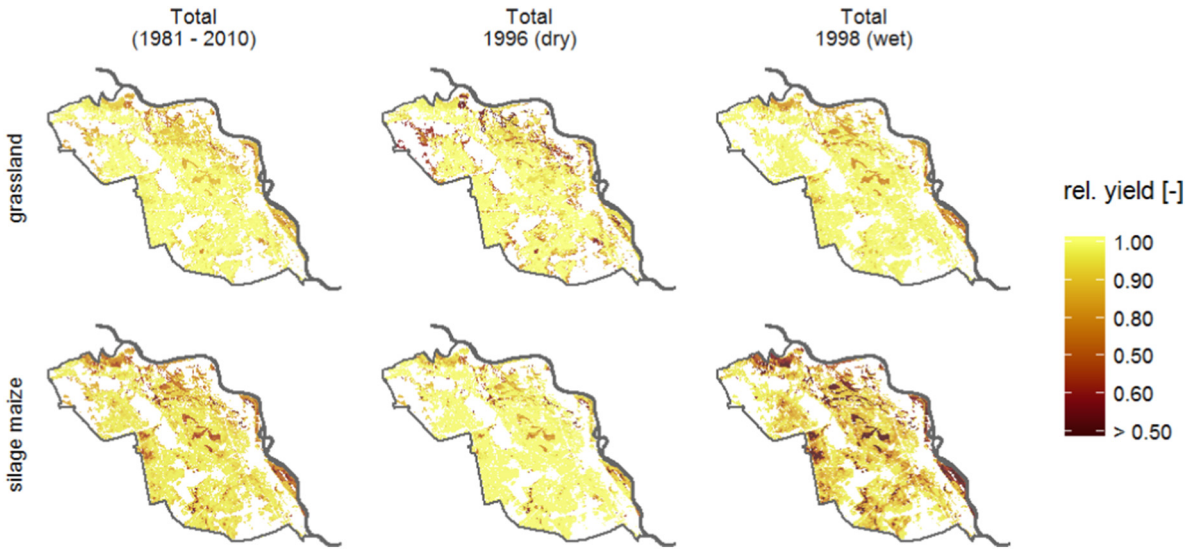

Fig. 7. 30-year average relative yield and relative yields for the years 1996 and 1998 for grassland (above) and silage maize (below) for pilot area De Raam as quantified with WaterVision Agriculture (WVA-table).

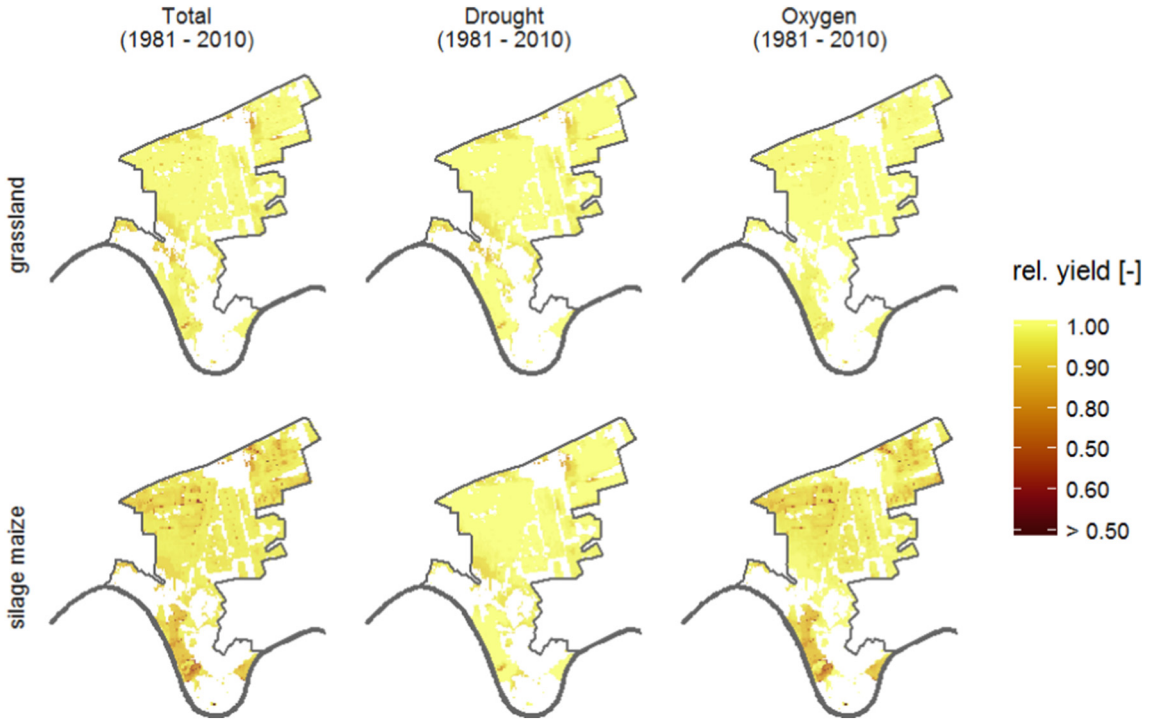

Fig. 8. 30-year average relative yield for grassland (above) and silage maize (below) for a region within pilot area De Vecht as quantified with WaterVision Agriculture (WVA-table). The relative yield is given as a percentage of the potential yield. The total relative yield is shown on the left, the part of this yield as affected by drought stress only is shown in the middle and the relative yield as effected by water excess only (i.e. oxygen stress) is shown on the right.

driest and wettest year within the series of simulated 30 years, namely 1996 and 1998 respectively. For grassland the results for a dry year show more crop damage than the long term average, but in a wet year grass yield is similar to the long term average. Fig. 7 also tells us again that silage maize yield is mostly affected by wet conditions. In a dry year relatively high maize yields are possible.

Similar to Fig. 6, but now for an area within the pilot region De Vecht, Fig. 8 shows the 30-year average relative yields for grassland and silage maize and also the distinction between drought stress and oxygen stress. Again, the conditions for grassland are quite good and for maize soil and groundwater conditions are sometimes suboptimal due to relatively shallow groundwater levels. For the river area near De Vecht hydrological measures are proposed that will lead to slightly higher groundwater levels. The effect on agricultural production can be assessed easily by applying the WVA-table. The water authority was also interested to know what could be the effect of climate change. Both effects are shown in Fig. 9 for both grassland and silage maize. Considering the proposed hydrological measures it is obvious that in most parts of the region there is no effect at all. Only near the river in the southern part of the area noticeable effects of these hydrological measures may occur according to the simulations. Especially for silage maize crop yields are expected to be lower due to wetter circumstances in the area close to the river. The results of the WVA-table for the climate scenario WH (KNMI, 2014) show that climate change might have

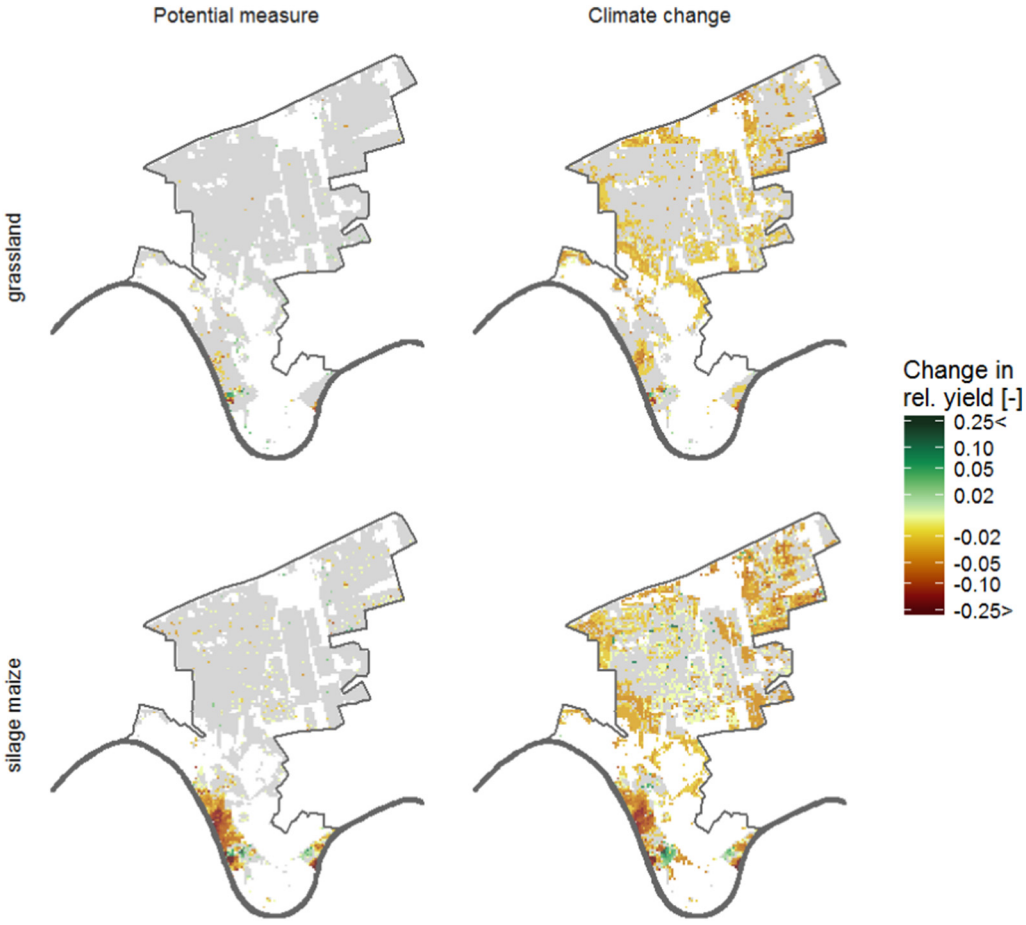

Fig. 9. Simulated changes in 30-year average relative yield for grassland (above) and silage maize (below) for a region within pilot area De Vecht as quantified with WaterVision Agriculture (WVA-table) as a result of either potential hydrological measures (left) or as a result of climate scenario WH (right). For grey areas no changes were found.

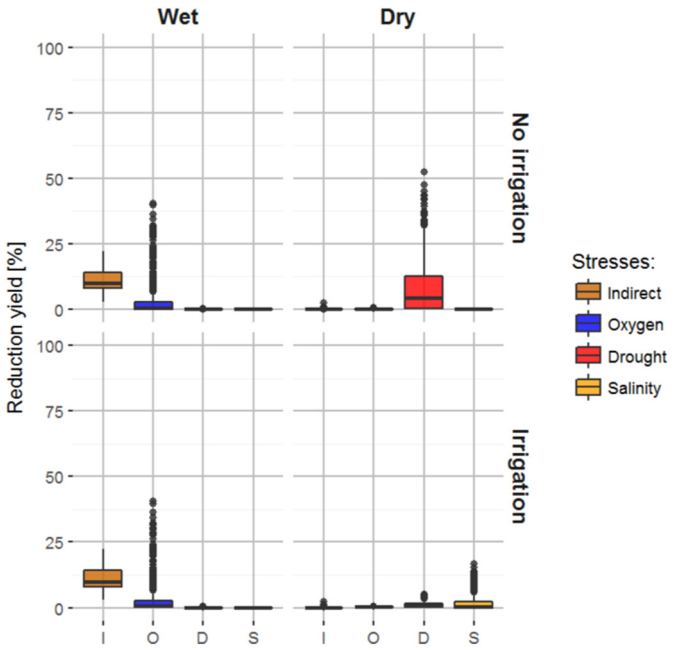

Fig. 10. Boxplot of simulated yield reduction for potato grown on a Cambic Podzol with a wet (left) and dry (right) groundwater regime. Each boxplot shows yield reduction as a result of indirect effects (brown), oxygen stress (blue), drought stress (red) or too saline conditions in the root zone (yellow). Results are shown without irrigation (above) and with irrigation (below). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

another additional effect. The differences between future and current climate are mainly caused by increased drought stress.

3.2. Results for saline conditions

Instead of looking at average results for an area as presented in Section 3.1, the model results can also be further analysed for a specific crop and soil type. An example of this is shown in Fig. 10 for potato and the most common sandy soil in the Netherlands. This soil type is a Cambic Podzol (IUSS Working Group WRB, 2015) with a topsoil of 20 to 30 cm with an organic matter content of 3 to 5%, and a clay content of 3%. The B and BC-horizon (from 20 or 30 to 60 cm below soil surface) contains 1 to 2% organic matter and the Cg-horizon (60–120 cm below soil surface) approximately 0.5%. We then focused on two specific groundwater regimes, a relatively wet type and a dry type. The wet type has a 30-year average highest groundwater (AHG) level at a depth within 40 cm below soil surface and a 30-year average lowest groundwater level (ALG) between 80 and 120 cm below soil surface. The dry type has an AHG between 80 and 140 cm below soil surface and an ALG deeper than 140 cm. The graph (box plots; Fig. 10) distinguishes indirect effects, drought stress, oxygen stress and salinity stress. The box plots show that wet conditions will result in indirect effects (due to workability problems) and in oxygen stress for the plant and on the other hand that drier conditions will result in yield reduction because of drought stress. When we allow irrigation in the simulation runs with varying salt concentrations Fig. 10 shows that for the dry groundwater regime the drought stress will be a lot less, but now sometimes yield reduction occurs due to saline conditions. The boxplots for the wet groundwater regime are the same for situations with and without irrigation as expected.

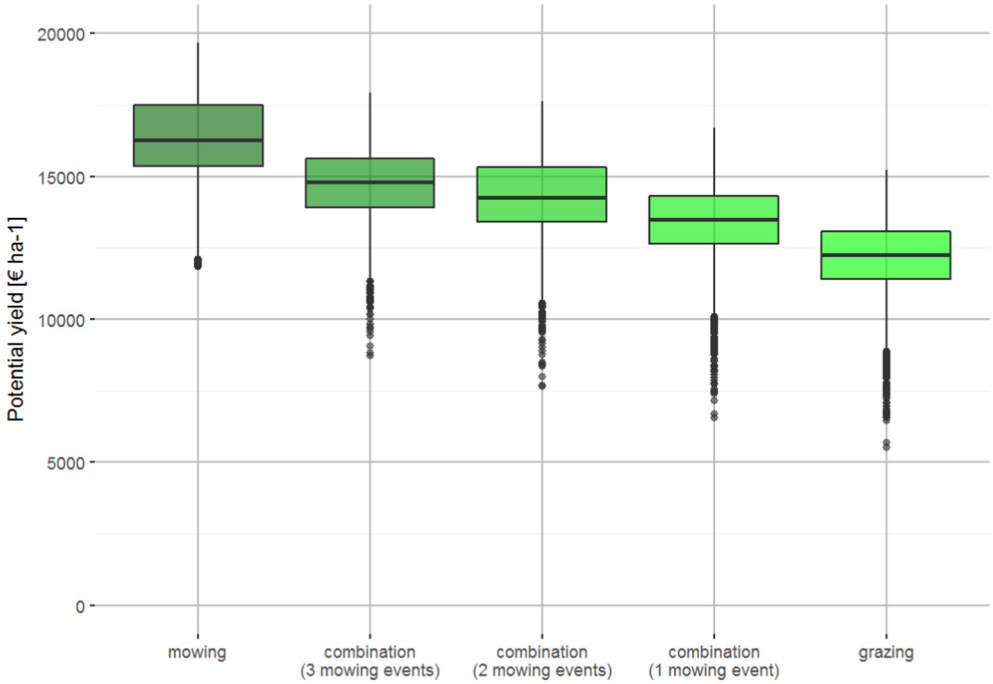

Fig. 11. Boxplot of simulated financial yield (€/ha) for grassland with varying grassland management.

3.3. Results of different grassland management in terms of economic effects

The results in Sections 3.1 and 3.2 are given in terms of agricultural yield or yield reduction, both in kg dry matter per ha. For specific applications, for instance when yield reduction because of drought which is induced by pumping up of groundwater by drinking water companies is to be compensated financially, it is more interesting to know the economic effect in financial terms. Fig. 11 gives an example for grassland showing also the effect of differences in grassland management. In this case the potential yield is shown and expressed in € per ha. This is calculated on the basis of the nutritive value and energy content of grass, depending on the moment within the growing season when the grass is cut or grazed. When grassland is only cut (mown) several times during the growing season the 30-year average yield for all simulations is highest and when grassland is only used for grazing the agricultural production potential will be lowest. In the Netherlands it is common that grassland is both cut and grazed within one season. The intensity of cutting and grazing defines the production potential both in dry matter yield as in financial result.

4. Discussion

The project WaterVision Agriculture aims at a climate-robust instrument that can determine crop yield effects as a result of drought, too wet or too saline conditions, based on process based models and an economic assessment. This instrument can be used at field level and the meta-model allows an application at regional level or national level showing long term effects or differences between years. As shown in this paper with some examples the instrument can be applied for decision makers to show the effects of climate scenarios or land use changes or changes in hydrology or combinations of these effects. We have also shown the possibility to focus on the results for a specific crop or soil type and to calculate effects in terms of kg dry matter or in € per ha. With these different components of WaterVision Agriculture we have made a toolbox for different applications as might be requested by the different end users, based on methods that are well known within quantitative land evaluation.

For decisions on land use it is expected that decision makers will use both WaterVision Agriculture and WaterVision Nature (Bartholomeus et al., 2018). This will enable them to take into account what will be the effect of their plans for both agricultural land and nature areas. Combining both instruments will provide insight in possibilities for optimal regional water management.

In the autumn of 2018 WaterVision Agriculture will be released for use by anyone who may want to apply the instrument. We expect many suggestions and requests for additions from all these users, and implementing further aspects based on these requests will enable us to improve the methods even further in order to enhance use for better decisions on sustainable soil and water management in current and future climate.

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